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INTRODUCTION
THE MICROECONOMETRICS OF DYNAMIC DECISION MAKING

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The study of individual economic behaviour in a dynamic setting has opened up new, exciting avenues of research. Economic theories of rational behaviour under uncertainty and in a dynamic setting often impose tight restrictions on structural empirical models of behaviour or require the solution of new and complicated estimation problems. Although these restrictions pose new and sometimes formidable hurdles for empirical researchers, the reward of clearing the hurdles is considerable. Once estimated, the structural models shed more light on economic theories than would be possible by more tightly specified models, and simulation of behaviour under new institutions or market conditions becomes possible.

In May 1994, the *Journal of Applied Econometrics* in collaboration with the CentER for Economic Research organized a conference on the Micro-Econometrics of Dynamic Decision Making at CentER. Most of the papers in this issue were presented at this conference. They are representative of the state of the art in the area and show both the difficulties and the benefits of this type of modelling.

Three papers in this special issue show the importance of dynamic models for understanding topics in resource and agricultural economics.

The paper by *Deaton and Laroque* examines the commodity price model: a dynamic model of equilibrium in the commodity market which accounts for restrictions on price paths induced by intertemporal arbitrage by risk-neutral commodity stockholders. This model traces it origins to the 'supply of storage' theories of Working (1949), Kaldor (1939) and Williams (1935). The theory posits that intertemporal arbitrage implies that stockholders will buy or sell from commodity stocks to drive current market price of a commodity p_t equal to the expected discounted price of the commodity next period, less the cost of storage. Deaton and Laroque assume that the cost of storage takes the form of proportional decay at rate δ. In equilibrium p_t must satisfy the following functional equation:

$$p_t = \max\left[P(x), \frac{1-\delta}{1+r}E_t p_{t+1}\right] \tag{1}$$

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where r is the risk-free interest rate and E_t denotes the conditional expectations operator given information at time t. The second term in the max expression in equation (1) reflects the impact of intertemporal arbitrage, which will be effective unless speculators expect net excepted discounted prices will be lower next period and there is a *stockout* which prevents them from selling off in which case the price of the commodity will be determined by ordinary supply price $P(x)$ from selling the entire available stock x of the commodity to demanders. The available stock x equals the sum of the net inventory $(1-\delta)I$ commodity stored in the previous period plus current production z.

Deaton and Laroque's paper focuses on the methodological issue of finding efficient numerical methods for computing approximate solutions to the functional equation (1) when harvests z_t follow a first-order Markov process. Similar to structural estimation of discrete dynamic programming problems (see e.g. the papers by Miranda and Schnitkey, Provencher, and Rust in this issue) structural estimation of the commodity price model requires a highly efficient 'nested fixed point' algorithm that recomputes an approximate solution to equation (1) each time the trial values of the structural parameters are updated by some 'outer' nonlinear estimation algorithm.

In previous work Deaton and Laroque developed a very efficient method for solving equation (1) in the special case where z_t is iid. They showed that the commodity price model in the iid case is capable of explaining a number of 'stylized facts' of commodity prices such as the tendency for prices to 'spike' asymmetrically in the upwards direction but not in the downwards direction (a big fall in prices signals expected gains from storage leading speculators to purchase commodities, but a big rise in prices may not be preventable if there is a stockout in a period of unusually high demand for the commodity). However Deaton and Laroque argue that the iid version of the commodity price model cannot account for the observed serial correlation in commodity prices. A natural way to account for serial correlation in $\{p_t\}$ is to assume that harvests $\{z_t\}$ are an AR(1) process. However, they show that this apparently benign assumption leads to formidable computational difficulties. In both the iid and the AR(1) cases the equilibrium price process $\{p_t\}$ can be derived from the solution to the functional equation (1). However in the AR(1) case the solution takes the form

$$p_t = f(x_t, z_t) \tag{2}$$

for some unknown function f, whereas in the iid case f depends only on the available amount of the commodity x_t. Deaton and Laroque's paper can be viewed as a nice illustration of the 'curse of dimensionality' that makes it vastly more difficult to compute approximations to f in the AR(1) case than in the iid case even though the functional equation (1) has considerable structure (e.g. it is a contraction mapping). They provide a very insightful discussion of the identification problem, and discuss full and limited information estimation of the structural parameters of the commodity price model. After an extensive investigation of alternative estimation and solution methods, they recommend pseudo maximum likelihood as the preferred estimation method and successive approximations using a discretization of the state space as the preferred method for approximating the solution f to equation (1).

Miranda and Schnitkey present a structural model of a farmer's decision whether or not to replace a dairy cow. They formulate a discrete dynamic programming model where the period equals the typical duration of a lactation cycle, or about 13 months. Milk production typically increases for the first three to four lactation cycles, then peaks and tends to decline in subsequent lactations. The problem is to determine an optimal policy for replacing older cows with young cows in order to maximize the expected discounted profits from milk production. Miranda and Schnitkey observed that 'Throughout the US dairy industry, observed rates of dairy cow replacement consistently exceed the rates prescribed as optimal by dairy economists'. Their structural model is able to fit actual dairy cow replacements quite closely, although the estimation results suggest that 'unobserved replacement premiums' are a key to the resolution to the puzzle. They suggest that transactions costs may be one explanation for these replacement premiums: their structural model used the market price of heifers (young cows) to determine the cost of replacement, but the authors note that the farmers in their sample grew most of their own replacement heifers. If there were significant transactions costs, the DP model would require a premium to compensate for replacing a heifer via the market than through 'internal replacement', so the 'replacement premium' could be explained by an overvaluation of the true cost of replacement. The other explanation is that the DP model abstracts from technological progress in dairy cow milk production, particularly due to genetic improvements. If so, their DP model would underpredict the expected net return to dairy cow replacement, requiring a 'replacement premium' in order to fit the data.

The Miranda and Schnitkey paper also makes an important independent methodological contribution. Following a general strategy promoted by Judd (1992) they approximate the value function $V(x, d)$ (the expected discounted profits of taking action $d \in \{0, 1\}$, 1 = replace cow, 0 = keep cow, for a cow in state x) as a linear combination of Chebyshev polynomials:

$$V(x, d) \simeq \sum_{i=1}^{m} c_{id}\phi_i(x) \tag{3}$$

where $\phi_i(x)$ is the ith Chebyshev polynomial. They develop an efficient and accurate algorithm finding approximate solutions to V by solving for a relatively small number m of Chebyshev polynomial coefficients. They show that under the parameterization (3) the Bellman equation equation reduces to a system of $2m$ equations in $2m$ unknowns (since there are two possible decisions, d). They show that this approach yields highly accurate solutions to the Bellman equation with far less computational burden than simple discretization methods which would have been huge in their case since the state x is four-dimensional with three continuous components (milk production, price of milk, and net replacement cost of a cow).

The paper by *Provencher* formulates and estimates a dynamic programming model of the optimal time to harvest a timber stand, a stochastic extension of the classic deterministic Faustmann model of the optimal time to cut down a tree. In previous work, Provencher estimated a DP model of timber harvesting decisions in North Carolina and showed that the stochastic version of the Faustmann model leaves us with a number of unresolved empirical puzzles. One of these puzzles is that his maximum likelihood estimates for the stochastic process of timber prices is close to a random walk whereas unrestricted estimation of timber prices leads to the conclusion that the actual prices are better approximated as an AR(1) process. Provencher showed that if the actual price process is AR(1), then 'adhering to a harvest policy that is optimal for a random walk price process reduces the value of bare forestland by 30%' (p. S58). Why did maximum likelihood of the full DP model push the AR coefficient to 1? Should we conclude that timber harvesters are dynamic profit maximizers but with irrational price expectations? Provencher re-investigates this issue using new quarterly data on timber harvests from a fairly homogeneous collection of slash pine plantations in south-eastern Georgia and north-eastern Florida. He replicates the puzzles that he noted about his previous estimation results using the North Carolina data, and in particular he finds that the estimated price process in the full structural model is close to a random walk even though unrestricted estimation of the price process rejects the random walk in favour of an AR(1) process. Provencher points out a number of important insights that can help pave the way to a resolution of these puzzles. First, he notes that the DP theory predicts that the optimal timber decision is independent of current price if the price process is a random walk but depends on current price if the price process is an AR process. Then he notes that unrestricted (or non-parametric) estimation of a model of actual timber harvesting decisions indicates that harvests are not significantly affected by timber prices. Thus, it appears that the DP model is forcing the price process towards a random walk in order to 'explain' the fact that harvest decisions do not depend on the price of timber. The 'unrestricted' choice model Provencher estimated can be viewed as shedding light on whether timber managers are behaving according to variety of simple, plausible, but potentially non-optimal 'rules of thumb'. He finds that actual harvest decisions are very well approximated by a simple volume-based harvest strategy, where the probability of harvesting is an increasing function of the volume of a timber stand, independent of current timber price. Since his dynamic programming model with irrational price expectations fits the data about as well as the simple volume-based rule of thumb, he concludes that 'Apparently there exists a large equivalence class of models consistent with the behaviour observed in the data' (p. S69). Overall, Provencher's results suggest that harvest decisions appear to be governed primarily by a set of non-price unobservable state variables in his data set, or in the terminology of this literature, due to stochastic variations in the 'convenience yield'. The reasons for these variations are not well understood, although Provencher notes that 'All managers emphasized that their primary objective is to ensure that the mill receives the wood it needs. None of them seemed to appreciate the potential gain from correctly forecasting timber prices' (p. S70). Provencher concludes that 'the analysis indicates that the stochastic versions of the Faustmann model now predominant in the forest economics literature are not particularly useful as positive models of firm behaviour. More fruitful would be solid empirical analyses to better understand the forces governing the random component of the convenience yield. Such analyses will require high-quality data that includes observations of the inventories of standing timber held by the firm' (p. S73).

We make one interesting methodological observation about this group of papers: all three papers used Chebyshev polynomial approximation methods to solve an underlying functional equation. While it turned out to be highly successful in Miranda and Schnitkey's and Provencher's applications, Deaton and Laroque did not find it effective for solving their functional equation (1) because they could find no way to guarantee the monotonicity of the Chebyshev polynomial approximations. Preservation of monotonicity is critical in their application since the law of motion for the available commodity stock x_t involves the inverse of the equilibrium price function f. Deaton and Laroque concluded that discretization of the state space was the only reliable way to guarantee the monotonicity and numerical stability of their fixed point algorithm. Preservation of monotonicity is not essential for the implementation of the solution and estimation algorithms in the Miranda and Schnitkey and Provencher papers. Neither author reported any 'wiggles' in their Chebyshev approximations to the value functions, and their numerical checks indicated that the approximate solutions closely approximated the solution to Bellman's equation over all points in the state space.

The paper by *Rust and Rothwell* uses a dynamic programming model of nuclear power plant (NPP) operations to study the impact of the March 1979 Three Mile Island (TMI) accident on the regulation of NPPs and its consequences for the operating behaviour and profitability of the US nuclear power industry. They treat the TMI accident as a 'natural experiment' that led to a permanent increase in the intensity of safety regulation by the US Nuclear Regulatory Commission (NRC) and increased scrutiny of operating costs by state and local public utility commissions (PUCs). One of the industry's responses to the shift in regime was to increase the planned durations between refuellings from 12 months in the pre-TMI period to 18 months in the post-TMI period. Rust and Rothwell's results indicate this was an optimal response since the optimal cycle lengths predicted by the DP model were approximately 12 months in the pre-TMI period and 18 months in the post-TMI period. Their structural estimation results also show that utilities have been responsive to the stricter NRC safety regulations in the post-TMI period by imputing a significantly higher cost to 'imprudent' operation of a reactor in the post-TMI period than in the pre-TMI period. Unfortunately, while they conclude that NPPs appear to be safer in the post-TMI period (in terms of having a lower rate of forced outages), they are also substantially less profitable: they estimate that over 90% of the expected discounted profits from continued operation of existing NPPs have been eliminated in the post-TMI period. However, since most of the investments in existing NPPs are already sunk and given the high costs of plant decommissioning, their DP model predicts that utilities would still rather continue to operate NPPs rather than shut them down.

The paper by *Bowlus, Kiefer, and Neumann* considers issues in the estimation of equilibrium wage distributions. As the authors note, there is an abundant literature on search models for job seekers. These models are typically of a partial equilibrium nature. In the prototypical model a job seeker receives job offers according to a Poisson process, where the associated wage is a drawing from some known distribution. The optimal strategy of a job seeker then has the reservation wage property: accept the job if the wage is above a certain level, the reservation wage, else keep searching. This approach to modelling leaves the demand side of the labour market in the dark. Only the behaviour of the workers supplying labour is modelled, not the behaviour of firms offering the jobs. Since the 1980s various authors have proposed equilibrium models of the labour market, where both sides are modelled and confronted.

In the estimation of such models various issues arise. First, the equilibrium wage distributions implied are often at variance with distributions observed in reality. For instance, the equilibrium wage density may be monotonically increasing. To repair this undesirable feature of equilibrium wage models, one may introduce heterogeneity among firms and/or among workers. That heterogeneity does play a role may be intuitively obvious. It is substantiated by Bowlus, Kiefer, and Neumann by running wage regressions with many controls and by looking at wage variation across workers in narrowly defined occupations. They find that heterogeneity plays a non-negligible role.

The starting point for the estimation of their structural model is the equilibrium search model developed by Mortensen (1990). If both workers and firms are homogeneous, the resulting distribution is tightly parameterized and at variance with reality. Allowing for worker heterogeneity does not improve things; the implied wage distribution would have regions of zero density. On the other hand, allowing for heterogeneity across firms changes the shape of the equilibrium wage distribution in a direction that looks more like the sort of distribution observed in practice. The authors therefore concentrate on an equilibrium model with homogeneous workers and a limited number of firm types differing in productivity. The number of different firm types, Q, has to specified *a priori*, but a Chi-squared test can be used to decide on the number of productivity levels that is consistent with the data. The implied wage density has a number of points of discontinuity equal to $Q-1$. Moreover, the jumps in the likelihood must occur at observed wages. This means that the points of discontinuity have to be found out of all possible $(Q-1)$ combinations of observed wages that could be the estimates of the points of discontinuity, and, of course, this search for points of discontinuity has to be repeated for every iteration on the parameters in the model. The authors choose simulated annealing in combination with Newton–Raphson to obtain the estimates. Monte Carlo experiments suggest that the methods work well.

The model is next used to estimate the distribution of weekly wages in the first jobs after graduation of white male high school graduates obtained from the NLSY. The estimation results suggest that there are about five productivity levels. The fit of the estimated wage distribution looks tight except at the lower tail.

The paper by *Koning, Ridder, and Van den Berg* starts from the same theoretical framework, but their approach to resolving the inconsistency between the form of the equilibrium wage distribution and what is observed in reality goes in exactly the opposite direction. In their paper they assume that there is a large number of markets in which workers and firms meet. Hence, even though within each market the equilibrium wage distribution has an upward-sloping density, any wage density observed in reality will be a mixture of many densities referring to different markets. To be more precise, it is assumed that every worker has a certain productivity denoted by p. The value of p for any individual is a drawing from a lognormal distribution function. Variation in p is the only source of non-observable heterogeneity considered and it might be said that every worker competes in his or her own market.

Another difference between this study and that by Bowlus, Kiefer, and Neumann is that the effect of minimum wages on the equilibrium distribution is explicitly accounted for. Given that data from the Netherlands are used, where a legal minimum wage exists and is relatively high, this aspect cannot be ignored. In the equilibrium model, one of the effects of a minimum wage is that whenever someone's productivity p is lower than the minimum wage he or she will be unemployed. This unemployment is structural, as opposed to the frictional unemployment that is the result of search and lay-offs.

A third contrast between this study and the study by Bowlus, Kiefer, and Neumann is the fact that panel data are being used. Hence both information on wages and on duration of unemployment or employment can be used to (over-)identify parameters.

A remarkable implication of the estimates is that a 10% rise in the minimum wage would raise unemployment by five percentage points. However, specification tests suggest that further improvements in the specification of the model are possible. In particular, the assumption of a lognormal distribution of productivities is too restrictive.

Magnac, Robin, and Visser consider alternative estimation strategies of transition models for incomplete individual employment histories. The motivation for their paper stems from the *Enquête Emploi de l'INSEE*, which is a rotating panel survey of the French labour force. In March of each year every individual in the survey is asked about the characteristics of his or her current occupation, and for how long he or she has remained in the reported state. Not only does this observation scheme lead to censoring, it also means that in certain cases spells are missed completely (namely if someone moved jobs twice between two consecutive interview dates). Although the authors discuss a structural model which could be generating the sort of data they are considering, all econometric analysis is concerned with reduced forms.

The estimation methods considered are Maximum Likelihood (ML) and Indirect Inference (II). Since ML may be quite complicated for the sort of observation scheme considered by the authors, II looks like a promising alternative. The basic idea of this method, introduced by Gourioux, Montfort, and Renault (1993), is to estimate parameters in two steps. First, one postulates some process generating the data, which is not the true one, but some approximation. Behaving as if the postulated process is the correct one, a set of so-called pseudo parameters is estimated by (pseudo-) ML. These pseudo-parameters bear a relation to the parameters of the true data-generating process. The relation between the true parameters and the pseudo-parameters can be approximated by simulation. This allows one to recover the true parameters from the pseudo-parameters.

In some Monte Carlo exercises the II-method appears to work well for the sort of problem considered. However, it turns out that on real data serious convergence problems occurred when optimizing the II-criterion with a Gauss–Newton algorithm. The reason is that the criterion is not differentiable in the parameters. A simplex-type algorithm did work but very slowly. Clearly more work has to be done before the II-method can be considered to be adequate for the kind of transition data analysed here.

The paper by *Aubin, Fougère, Husson, and Ivaldi* analyses data of a very interesting peak load pricing experiment in France. *Electricité de France* (EDF) offers participants in the experiment electricity prices that vary by time of day and across days. Three 'types' of day are distinguished in a year: 300 blue days, 43 white days, 22 red days. The blue days are the cheapest ones, the red days are the most expensive ones. To mention one example, on red days the peak electricity price is over ten times higher than on blue days. Although households know how many days of each colour there are in a year, they do not know when these days will be. They are told the colour of a day on the evening of the day before. Typically, white and red days are days in very cold periods, when electricity use is highest. The effects of the price differences across types of days were substantial: the average daily consumption on red days was less than the daily consumption on white days, which in turn was less than on blue days.

As a theoretical framework for the modelling of household behaviour it is assumed that households try to maximize expected discounted utility. Utility only depends on peak and off-peak electricity consumption (i.e. this consumption is separable from the consumption of other goods). The functional form of the utility function is chosen such as to arrive at Frisch demand functions, which can be estimated by ML. Once the parameters of the utility function have been estimated, can not only calculate elasticities but also the welfare effects of various pricing systems. The authors conclude that for most customers the experimental pricing scheme has produced a welfare gain.